Article

Yield and quality of strawberry fruit grown in a greenhouse in a pyramidal hydroponic system

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Abstract

Strawberry (*Fragaria* x *ananassa* Duchesne) is an important crop in Mexico and the world. To increase yields, various production systems have been explored, such as hydroponic systems. The objective of this study was to determine the effect of strawberry cultivars, planting densities and strata in a pyramidal hydroponic system, on plant development, production and fruit quality. The study was carried out in Salinas de Hidalgo, SLP, Mexico, in the spring-autumn cycle of 2017. The stratum factor impact on the development and yield of the crop, with the high stratum the number of leaves, crown width, increased number of fruits and yield (23.5 kg m^{-2}), and quantity of soluble solids in comparison with the lower ones. The plants in the intermediate strata were less productive, probably due to the shade caused by those in the higher strata. Density and cultivar had no significant effect on fruit development, yield and quality.

Keywords: *Fragaria* x *ananassa* Duchesne, greenhouse, plant density, vertical production systems.

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Introduction

There is growing interest in the inclusion of strawberries, especially strawberry, in people's daily diet, mainly due to the health benefits associated with their consumption (Çolak and Alan, 2017). In 2008, worldwide, strawberries were cultivated on 322 630 ha with a production of 5 978 807 t, in 2018, it was cultivated on 372 361 ha, with an annual production of 8 337 099 t. Currently, Mexico is the third producing country, after China and the United States of America, with 7.8% of world production. In 2018, 13 652 ha were planted in Mexico with a production of 653 639 t (FAOSTAT, 2020).

Intensive production techniques such as hydroponic systems have increased their use (Hernanz *et al*., 2008). One of the most promoted cultivars in Mexico is 'Festival'; this cultivar has a short photoperiod, conical shaped fruit and an intense red color (Chandler *et al*., 2000). The recently introduced cultivar 'San Andreas' has a moderately neutral photoperiod, with little need for cold in the nursery (Eurosemillas, 2020).

López-Pérez *et al*. (2005) mention that in the 1990's, various ways of increasing the yield of strawberry cultivation under traditional soil conditions were explored. Currently, hydroponic systems are used, due to their benefits with the more efficient use of fertilizers and pesticides (Keutgen and Pawelzik, 2007), high densities, adequate balance of nutrients (Sánchez del Castillo *et al*., 2014) and water (Van Ginkel *et al*., 2017), higher yield (Paranjpe *et al*., 2008; Tariq *et al*., 2013) and fruit quality (Caruso *et al.*, 2011).

In these systems, water can be used as a culture medium or different substrates, such as rock wool, coconut fiber or perlite; fertilization is through nutritive solutions (Kratky, 2005). Strawberry density in soil is 6.5 to 8 plants m^{-2}, while in vertical hydroponic systems it can be up to three times higher (Ozeker *et al*., 1999). Such as metal racks and vertical bag arrangements, being able to produce most horticultural crops, such as lettuce, tomatoes, and strawberries (Benke and Tomkins, 2017).

Strawberry production can increase with increasing plant density. Paranjpe *et al*. (2003) obtained yields of 9 kg m^{-2} in a greenhouse without climate control with a density of 20 plants m^{-2} grown in bags with substrate in Florida, USA. There are several studies on fruit quality in strawberries grown in hydroponic systems (Cecatto *et al*., 2013; Karimi *et al*., 2013), as well as on the influence of the substrate on fruit production and quality (Recamales *et al*., 2007; Palencia *et al*., 2016; Martínez *et al*., 2017). The objective of this study was to determine the effect of strawberry cultivars, planting densities and planting strata in a pyramidal hydroponic system, on plant development, production and fruit quality.

Materials and methods

The study was carried out in a two-tunnel greenhouse, with manual side windows, a height of 5 m at the dome, and an area of 756 m^2, without climate control. The air temperature and relative humidity of the greenhouse were measured with sensors connected to a datalogger (Hobo, model U23 V2). The greenhouse is located in the municipality of Salinas de Hidalgo, San Luis Potosí, Mexico [22° 37' 39'' north latitude, 101° 42' 52'' west longitude; altitude of 2 070 m (INEGI, 2020)].

The cultivars used were 'Festival' and 'San Andreas'. The bare root plant was acquired with producers from the municipality of Pabellón de Arteaga, Aguascalientes, Mexico. It was kept refrigerated at 3 °C for 60 days before transplantation for storage. It was planted on March 10, 2017 directly. To establish the experiment, the construction of the hydroponic system and the placement of the horizontal bags with coconut fiber began.

The pyramidal system was manufactured with a steel structure, with three metal tubes 1.5 m long each, the triangles have eight short tubes of 0.22 m, welded to the sides at four heights every 0.5 m, which are used to place two sections of 1 m long tube, which function as a base to place the bags (Figure 1). Each repetition was made up of three modules. The horizontal bags with coconut fiber are Germinaza® with the mixture of 50% powder and 50% fiber, 1 m long by 0.2 m wide with a volume of 18 L. 24 horizontal bags were used per repetition.

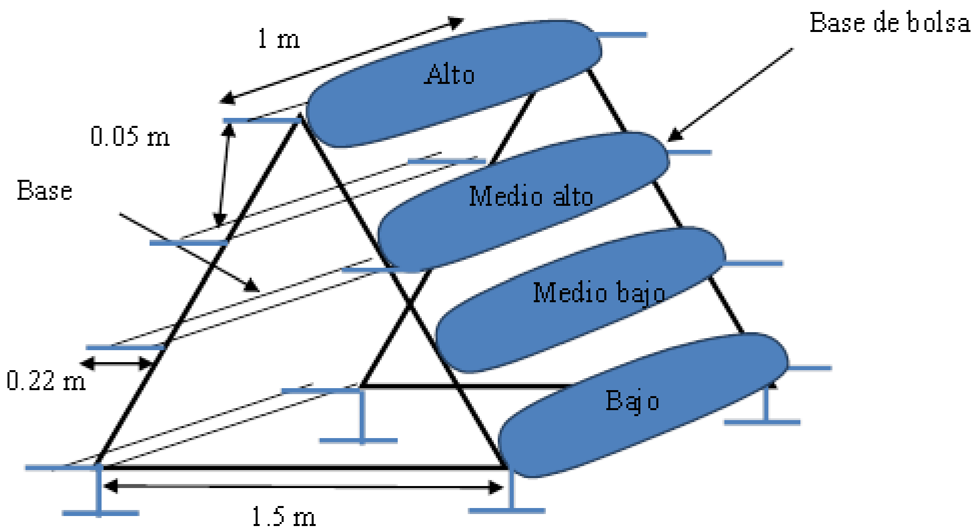

Figure 1. Diagram of the pyramidal hydroponic module, with the structure and horizontal bags located in four layers.

The irrigation system consisted of a 0.5 L h^{-1} flow band and a distance between drippers of 10 cm, connected to a ¼ hp pump by means of a 16 mm hose. The system was automated to give 2 or 3 irrigations per day as required by the crop. The fertigation system was supplied with nutrient solution by a 2 500 L reservoir.

Regarding the handling of the nutrient solution, during the first three days it was watered only with rainwater, later it was watered with nutrient solution. Trays were placed to collect drainage and control drippers in each of the strata, measurements of volume, pH and electrical conductivity were carried out twice a week from April 15 to October 6, 2017.

The nutrient solution of Hewitt and Smith (1974) and Caruso *et al*. (2011). Through the fertilizers: potassium nitrate (KNO_3), calcium nitrate ($Ca(NO_3)_2$, monopotassium phosphate (KH_2PO_4), magnesium sulfate heptahydrate ($MgSO_4$ $6H_2O$), potassium sulfate (K_2SO_4), as a source of micronutrients, a commercial mixture called Tradecorp® AZ. The pH of the nutrient solution was maintained at 6 ±0.3, and electrical conductivity of 1.3 dS m^{-1} in the vegetative stage (1 to 20 weeks after transplantation, SDT) and 1.5 dS m^{-1} in the reproductive stage (21 to 30 TDS) applied in a range of 100-400 mL $plant^{-1}$. The supply of nutrients was managed with an open system.

For pest control, sanitation pruning was carried out every two weeks, in which old leaves and those with pest damage were removed. From May to August, the insect *Tetranychus urticae* was controlled by means of abamectin alternated with cypermethrin in doses of 1 ml L^{-1}. The development variables measured were: number of leaves and crown diameter. The diameter was measured from the wide part and the multiple crowns of the plant were considered as one (Cantliffe *et al*., 2007). The variables were measured every two weeks from May 5 to October 6, 2017.

The variables quality and fruit production were determined in each harvest by measuring: diameter with a digital vernier and the content of soluble solids of the fruit with an optical refractrometer Atago Brix 0.0 to 33%) from the fruit juice, according to the standard NMX-FF-062-SCFI-2002, fruit weight and fruit yield (per plant and square meter). The fruit harvest was carried out every week starting on July 28 and ended on October 6, 2017.

The experimental design was in randomized complete blocks with 24 treatments and three repetitions with factorial arrangement. The factors tested were: (a) two strawberry cultivars (‘Festival’ and ‘San Andreas’), (b) three plant densities per horizontal bag (6, 8 and 10, corresponding to 33.2, 25 and 20 linear cm between plant with double row of staggered plant and equivalent to 32, 43 and 53 plants m^{-2}, respectively) and (c) four strata in the pyramidal system (high, medium high, medium low and low). Data were taken from two plants per experimental treatment with a total of 72 data for each variable.

The statistical analysis of the results was carried out using a general linear model, a regression procedure using the statistical program SAS version 9.4. With Tukey’s mean test at 95% confidence.

Results and discussion

Cultivar factors and plant density

There was no significant effect in any of the variables evaluated for the factors: cultivars and plant density, nor for any of the interactions; there was only a significant effect for the stratum factor of the plants in the hydroponic system. Therefore, the results presented correspond to this factor.

Stratum factor

Development variables: between 8 and 19 SDT the plants showed vegetative behavior, with no difference between treatments in the four strata. After 20 SDT the differences began for: number of leaves (Figure 2), crown diameter (Table 1), fruit diameter (Table 2) and number of fruits (Table 3).

The plants of the upper stratum had a greater number of leaves (Figure 2A). According to the regression analysis, after week 30, the number of leaves increased in the upper stratum, contrary to what was observed in the lower strata (Figure 2B).

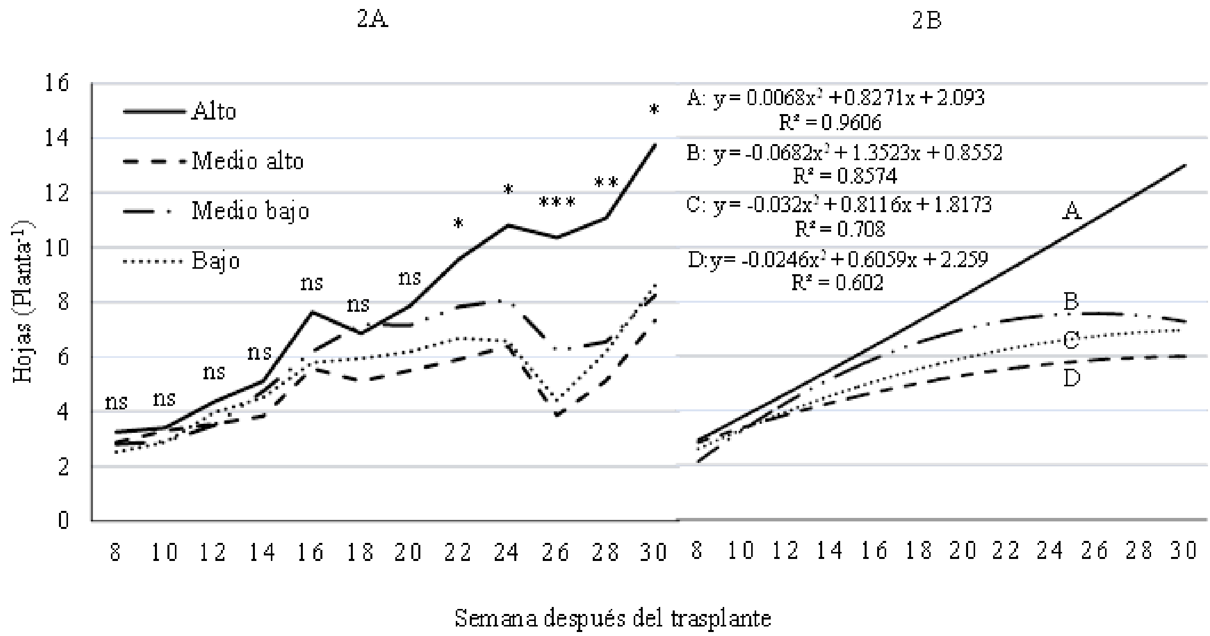

Figure 2. Number of leaves per greenhouse strawberry plant produced in four different strata in a production system with a pyramidal structure. 2A) the curves connect the means, data evaluated by analysis of variance (General Linear Model, SAS); 2B) curves calculated by linear regression. ^{ns}, *, **, *** not significant and significant at $p \leq$ 0.05, 0.01 and 0.001, respectively.

In the upper stratum, the number of leaves was 13 leaves at 30 SDT; this value is less than the 16 leaves per plant reported by Juárez-Rosete *et al*. (2007) in a horizontal NFT system at 10 SDT, where he mentions that the NFT being a circulating (closed) system is given a constant supply of nutrients unlike open substrate systems. In addition to this, Díaz-Pérez (2013) mentions that under shade the productivity of crops can be reduced.

This agrees with our results where fewer leaves and a reduction in crown diameter were observed in the shaded strata. The inclination of the pyramidal system could cause the plants to be shaded to a greater extent in the intermediate strata. The smaller size of the intermediate strata causes that the plants of the lower strata had greater exposure to light, since the inclination prevents the plants with less growth, in this case the plants of the intermediate strata, from affecting the development of the plants in the lower stratum.

At 26 SDT, a decrease in the number of leaves was observed, this due to the sanitation pruning that was given to stimulate the formation of new foliage and flowers, thereby avoiding the formation of stolons, since it is one of the reasons why the plant strawberry loses nutrients and photosynthesized compounds (Avitia-García *et al*., 2014).

The regression analysis showed an increase in the number of leaves in the upper stratum compared to the three lower strata, it is the only one that shows an increasing behavior, with an R^2= 0.9606. The results of the diameter of the crown agree with the behavior of the number of leaves, in most cases, the largest diameter was presented in the upper stratum of the plants with a 77% increase compared to the intermediate strata, where it was lower (Table 1).

Table 1. Strawberry crown diameter for two cultivars in four strata in a pyramidal hydroponic production system, planted in horizontal bags.

Stratum factor	Weeks after transplant					
	20	22	24	26	28	30
High	2.43 a[†]	2.61 ab	2.66 a	2.63 a	2.77 a	3.09 a
Medium high	1.81 bc	1.96 ab	2.03 ab	2.06 ab	2.04 ab	2.15 bc
Medium low	1.48 c	1.53 b	1.69 b	1.5 b	1.54 b	1.46 c
Low	2.1 ab	2.77 a	2.37 ab	2.65 a	2.82 a	2.93 ab
p	0.0004	0.0213	0.0042	0.0017	0.0008	0.0001

[†]= different letters within the column indicate significant differences according to Tukey's test (p= 0.05).

The diameter of the crown in the upper stratum ranged from 2.43 cm in week 20 to 3.09 cm in week 30, with an average growth per week of 0.06 cm, greater than that reported by Tariq *et al*. (2013) where he obtained diameters from 1.06 to 1.4 cm testing different densities of plants and substrates in strawberry hydroponics, where the largest diameter was obtained with a mixture of sand, manure and silt substrates (1:1:1) with a density of plants of 22 plants$\cdot$m^{-2}. In the upper middle stratum, an increase in the diameter of the crown of 0.03 cm per week was observed, which corresponded to half the average in the plants of the high stratum, and in the lower middle stratum the same size was maintained among these 10 weeks (20-30 SDT).

In the same way as in the variable number of leaves, light could influence (Díaz-Pérez, 2013) the size of the diameter of the crown, since, the lower the number of leaves, the less the thickness of the crown in the strawberry plant. Flowering started 20 SDT. However, Hidaka *et al*. (2017) report that strawberry flowering begins at 6 SDT. In this study, the delay in flowering could be attributed to the high temperature and a long photoperiod, since the low temperature and short days induce flower differentiation (Miyoshi *et al*., 2013).

Inside the greenhouse, the average maximum temperature (TMaxP) during the months of March to June was 35 °C and the average minimum (TminP) 15 °C, from July to October the TMaxP was 32 °C and the TMinP 14.5 °C. The minimum and maximum recorded throughout the crop cycle were 4 °C to 38 °C, respectively. Neri *et al*. (2012) mention that the development of flower buds in an early stage is carried out in an optimal temperature range of 26.7 °C day/15.6 °C night, so that high temperatures partially inhibit flowering (greater than 26 °C) or totally (greater than 30 °C).

Fruit quality and yield variable: these variables registered behavior similar to that described in number of leaves and crown diameter; that is, only the stratum factor had a significant effect. The plants located in the upper part with respect to the plants of the medium-high and medium-low stratum presented greater fruit diameter (Table 2). The plants of the high stratum produced statistically the same number of fruits (Table 3), that those of the low stratum in the 22 and 24 SDT, with a tendency to be higher in the high stratum. In the medium-low stratum the diameter of the fruits was smaller than the upper stratum from 22 to 30 SDT.

Table 2. Fruit diameter in two strawberry cultivars as a result of four strata of plants in horizontal bags in a pyramidal hydroponic system.

Stratum factor	Weeks after transplant					
	20	22	24	26	28	30
High	1.48 a†	1.88 a	2.11 a	1.84 a	1.79 a	1.95 a
Medium high	0.58 a	0.65 b	0.82 b	0.94 ab	1.09 ab	1.08 ab
Medium low	0.62 a	0.73 b	0.51 b	0.67 b	0.68 b	0.69 b
Low	1.07 a	1.16 ab	1.41 ab	1.22 ab	1.62 ab	1.47 ab
p	0.0604	0.006	0.0001	0.0283	0.0337	0.0107

†= different letters within columns indicate significant differences with Tukey' test (p= 0.05).

Table 3. Number of strawberry fruits per plant in two strawberry cultivars as a result of four strata with horizontal bags in a pyramidal production system.

Stratum factor	Weeks after transplant					
	20	22	24	26	28	30
High	3.33 a†	5.88 a	7 a	6.66 a	6.77 a	6.44 a
Medium high	1.22 a	1.33 b	2.66 b	2.66 b	2.88 a	3.33 a
Medium low	1.33 a	2 b	2.22 b	1.88 b	3.77 a	4 a
Low	2.88 a	3.55 ab	4.66 ab	4.44 ab	3.88 a	6.33 a
p	0.0561	0.002	0.0071	0.0042	0.1805	0.2595

†= different letters within the column indicate significant differences according to Tukey's test (p= 0.05).

The yield was higher in the upper stratum of the pyramid, except in week 30 where the plant yield was similar to the low stratum (Figure 3A). The plants of the low stratum had an upward trend in yield, while the curve of the high stratum had a decreasing behavior at the end of the experiment (Figure 3B). According to Ledesma *et al*. (2008), the temperature and the length of the day play a fundamental role that affects the production of fruits. Ledesma and Kawabata (2016) mention that there is a decrease in fruit size and weight caused by high temperatures (greater than 32 °C for more than 4 h) in strawberry cultivars, temperatures less than 2 °C and greater than 35 °C for prolonged periods, cause devitalization of pollen, floral abortion and fruit malformations.

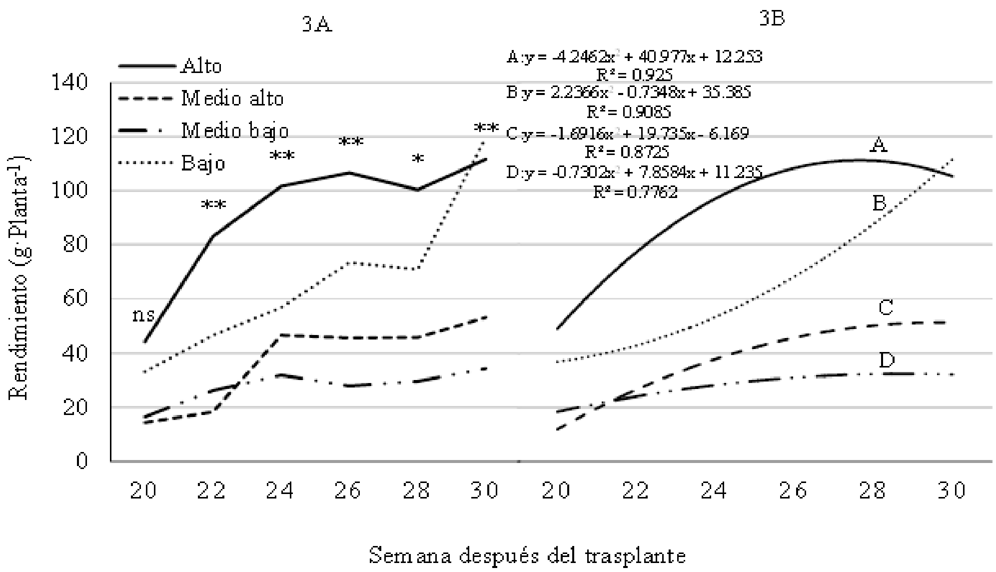

Figure 3. Cumulative yield of greenhouse strawberry fruits produced in four different strata of production system with pyramidal structure. 3A) the curves connect means; data evaluated by analysis of variance (General Linear Model, SAS); 3B) curves calculated by linear regression. $^{ns, *}$, **, *** not significant and significant at $p \leq$ 0.05, 0.01 and 0.001, respectively.

Probably the 'Festival' and 'San Andreas' cultivars responded favorably to high temperature stress, since from July to October there were maximum temperatures of 38 °C, but lasting less than 4 h. Caruso *et al*. (2011) report that the duration of high temperature stress in strawberry affects the number of fruits. These authors mention that the period in which the plant is cultivated has great relevance for strawberry production, since cold hours are crucial for strawberries, in agreement with our study, since probably the excessive accumulation of cold hours also prevented the plant will develop in better conditions.

The total soluble solids were only different in the 24, 26 and 30 SDT in the treatment with the high and low stratum where the highest values (better quality) are had, although statistically the values of the medium high and medium low stratum were not different of the lower stratum (Table 4).

Table 4. Total soluble solids in the fruits of two strawberry cultivars, produced in four strata in horizontal bags in a pyramidal hydroponic system.

Stratum factor	Week after transplant					
	20	22	24	26	28	30
High	5.6 a†	7.3 a	8 a	7.4 a	6.7 a	7.3 a
Medium high	2.1 a	6.9 a	3.1 b	2.8 b	3.8 b	4.5 ab
Medium low	2.5 a	2.8 a	1.9 b	2.8 b	2.8 b	2.4 b
Low	3.4 a	4.3 a	5.2 ab	4.9 ab	6.1 a	6 ab
p	0.06	0.5704	0.0002	0.0061	0.0369	0.0132

†= different letters within the column indicate significant differences according to Tukey's test (p =0.05).

The total soluble solids were higher when the yields increased (Figure 4), the yield also increased when the incidence of solar radiation increased. Solar radiation is associated with the content of soluble solids in the fruit. Díaz-Pérez (2014) reported that the amount of total soluble solids decreases when the shade level increases in bell pepper (*Capsicum annuum* L.). Thus, by having greater shading in the medium-high and medium-low strata, there is a lower amount of soluble solids in the fruit, stratified in the same way as the other variables observed.

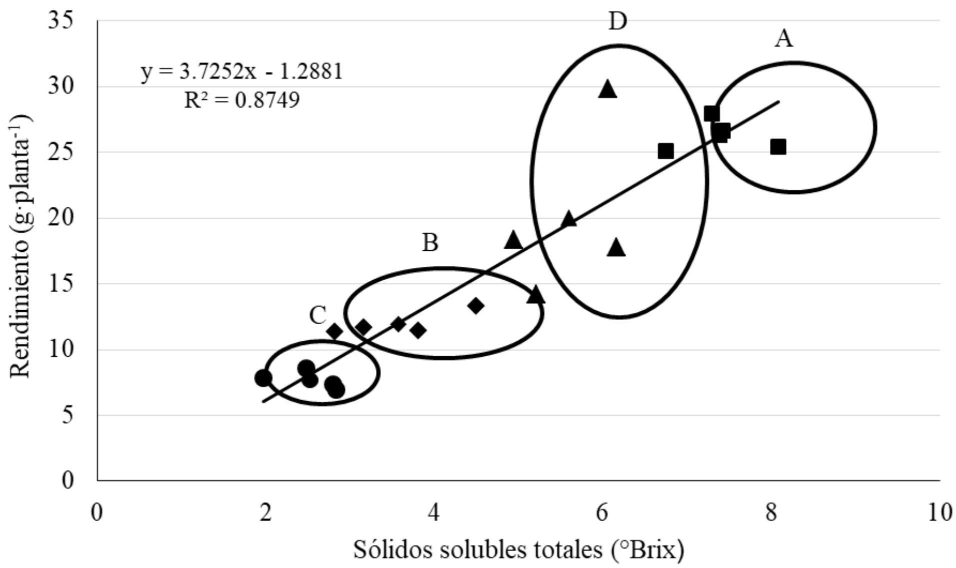

Figure 4. Relationship between total soluble solids and yield as a result of four strata with horizontal bags in a pyramidal hydroponic system; through, linear regression analysis. A= high, B= medium high, C= medium low, D= low.

The yields obtained per plant agree with the trend in the variables: number of fruit and diameter of fruit, since the high, medium-high and medium-low stratum has the same decreasing behavior in yield per plant, adjusting to the probability that the shadow acted on the system by making a pattern over the three strata in which it shows us that the variability of light that affected the system affected the plants as a whole, this agrees with that reported by Wang and Wang (2014) as it mentions that light intensity is a key factor in improving strawberry production in a hydroponic system.

The production results in this study were low compared to those presented by Miranda *et al*. (2014) in a hydroponic system in bags and coconut fiber channels since they obtained 684 and 1 407 g plant^{-1} handling a density of 10 and 13 plants m^{-2}, respectively. However, the total yield was higher in this study. Since using a density of 43 plants m^{-2}, a production of 23.5 kg m^{-2} was obtained in the upper stratum of the pyramidal system (Table 5), therefore, one of the benefits of the pyramidal system is the ability to increase the plant density per square meter and space optimization.

Table 5. Cumulative strawberry yield per plant and per square meter in two strawberry cultivars as a result of four strata in a pyramidal hydroponic system.

Stratum	Yield	
	(g $plant^{-1}$)	(kg m^{-2})
High	547.63 a†	23.5 a
Medium high	223.49 b	9.6 b
Medium low	165.99 b	7.1 b
Low	400.41 ab	17.2 ab
p	0.0007	0.0007

†= different letters within each column indicate significant differences according to Tukey's test (p= 0.05).

The results obtained in this study were also higher than that reported by Paranjpe *et al*. (2003), in this case per square meter, since it reported a yield of 7 to 9 kg m^{-2} in a hydroponic system, in a greenhouse with climate control, with production in the winter months in Florida, USA.

Conclusions

The development of strawberry plants in the pyramidal system showed that the cultivars 'Festival' and 'San Andreas'; and densities 6, 8 and 10 plants per bag did not show significant differences between treatments. The pyramidal system showed that in the upper stratum the plants had greater: number of leaves, diameter of the crown, diameter of fruit, number of fruits, soluble solids content and yield.

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